Furrow Formation on Ganymede and Callisto: New Evidence from Galileo.

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As some of the oldest tectonic features on Ganymede and Callisto, furrow systems can provide valuable information about the state of the lithosphere at the time of their formation and its subsequent thermal evolution (1 - 3). We present new results from Galileo of the furrow systems in Galileo Regio, Ganymede, and the multi-ring systems of the Valhalla and Asgard impact basins on Callisto. Furrows on Ganymede are found only in the older, heavily cratered dark terrain. Three main systems of furrows have been identified from Voyager data with different primary orientations and ages. Using the classification system of Murchie et al. (4), Systems I and II are found in the anti-Jovian hemisphere, in both Marius Regio and Galileo Regio. System I furrows predate those of System II and are generally interpreted to be of impact origin (4-6). Murchie et al. (4) suggest that these furrows are reactivated impact basin rings. There has been some discussion as to the origin of System II furrows; Murchie et al. (4) interpret these to be the surface expression of isostatic adjustment over a large-scale mantle thermal anomaly, while other workers consider them to be of impact origin.

Callisto possesses at least 8 systems of concentric and radial fracture zones arranged around degraded palimpsests (7). These are interpreted to be impact structures. The two largest tectonic structures on Callisto's surface are the 2000 km Valhalla basin, and the 800 km Asgard basin. Cratering models indicate that furrows on Ganymede may only be 100 - 200 m.y. younger than Valhalla (7), therefore direct morphological comparisons are reasonable.

Morphology and characteristics of furrows: Observations of Voyager data showed that furrows on Ganymede have relatively wide, flat floors, are bounded by sharp, raised rims and are widely spaced. Individual furrows range from 50 to several hundred km long, are 5 - 10 km wide (8) and the interfurrow spacing is fairly uniform at ~ 50 km, although the furrows are generally closer together near the center of a furrow system (7).

Valhalla exhibits an inner ridge and trough zone extending approximately 950 km from the center of Valhalla, and an outer scarp or graben zone, extending to 1500 - 1800 km (9). The outermost rings around Valhalla have been interpreted as outward-facing scarps (10, 2), and more recently as graben structures, with outward-facing scarps in the north-east sector (9). Individual Valhalla ridges are ~200 - 500 km in length, irregular in plan and average ~15 km in width (9). Spacing between the rings increases with distance from the center of both Valhalla and Asgard (7, 9). Heights of the Valhalla ridges have been estimated at <1 km above surrounding surfaces, while those of Asgard have been determined to rise 500 m to 1 km above the surrounding surface (7).

Questions and issues to be addressed by Galileo: Outstanding issues to be addressed by Galileo imaging include the determination of the true size of Valhalla; the presence or absence of a strike-slip zone around the distal portions of Valhalla which would provide evidence for a cratering model of plastic asthenospheric flow (10); the nature of the distal zone around Valhalla, whether outward-facing scarps or graben, and the spatial extent of each of these; comparisons between the ring systems of the Callisto impact basins and the furrow systems on Ganymede proposed to result from large impacts; comparisons between the furrows of Ganymede's System I and System II to define the distinguishing characteristics between two furrow systems which look broadly similar but which may have very different origins; the nature of the furrow rims on both satellites and information this provides regarding the extent and effectiveness of isostatic adjustment at the time of formation and subsequent evolution; and general information from faulting regarding the thermal state of the satellite surfaces at the time of furrow formation. During the G1 orbit, an area (~150 km x ~120 km) of Galileo Regio on Ganymede was imaged at a resolution of ~80 m/pixel. The G2 orbit provided stereo coverage at a comparable resolution over about one-third of the same area. During the G2 orbit, degraded furrows were also imaged (at 90m-115m/pixel) in transitional terrain, on the boundaries of Nippur Sulcus, and around groove lanes in Marius Regio. The C3 orbit imaged the Asgard impact structure at a resolution of 1.1 km/pixel, and portions of the Valhalla graben and scarps at the resolutions of 42 m/pixel and 37 m/pixel respectively.

Galileo observations of furrows on Ganymede: The two primary furrow systems (4) are seen within Galileo Regio, where a System II furrow clearly cross-cuts a System I furrow. Using stereo data we have constructed profiles across the two main furrows in the study area (figure 1). Profiles 1 - 7 (figure 2) are taken across a System II furrow and 8 - 14 (figure 3) across an older System I furrow. Profiles 1 - 7 show rims which rise from ~200 to 1200m above the furrow floor and <900 m above the surrounding terrain. Rims range from ~3 to ~5 km in width. The western wall is highest at the junction where this furrow starts to cross-cut the NW-SE-trending furrow of System I (profile 4). This is consistent with isostatic adjustment of the two furrow rims. At its northern end, the floor of the furrow is 'V'-shaped, but at its center, where the two sets cross, the floor is relatively flat and wide, measuring 5 km. Wall slopes range from 2˚ - 38˚ on the western walls and 6˚ - 30˚ on the eastern walls. Average slopes are 20˚ and 15˚ on western and eastern walls respectively. Profiles 8 - 14 are taken across the NW-SE -trending System I furrow. This furrow is much more degraded in appearance and profile than the System I furrow which cross-cuts it.

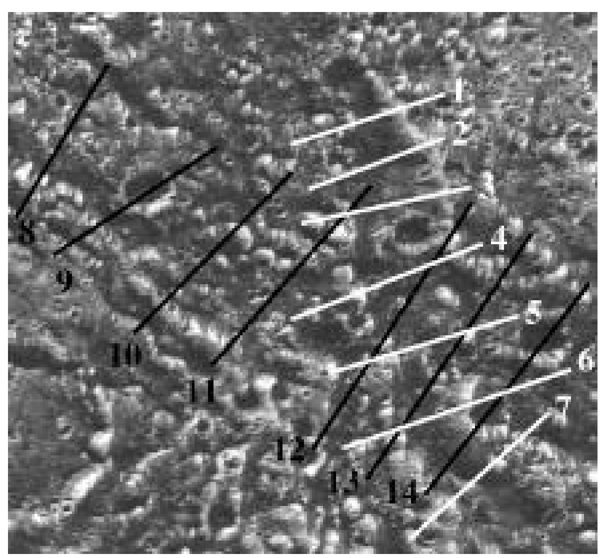

Figure 1: System I and II furrow profiles.

The south-western rim of this furrow is still relatively unbroken but the north-eastern rim is comprised of discontinuous bright knobs and in some places is absent altogether. Slopes range from 3˚ -13˚ on the western walls and 2˚ - 10˚ on the eastern walls, with average slopes of 9˚ and 6˚ for the western and eastern walls respectively. The furrow floor varies from 'V'-shaped to flat, in which case it measures <10 km across (e.g. profile 11).

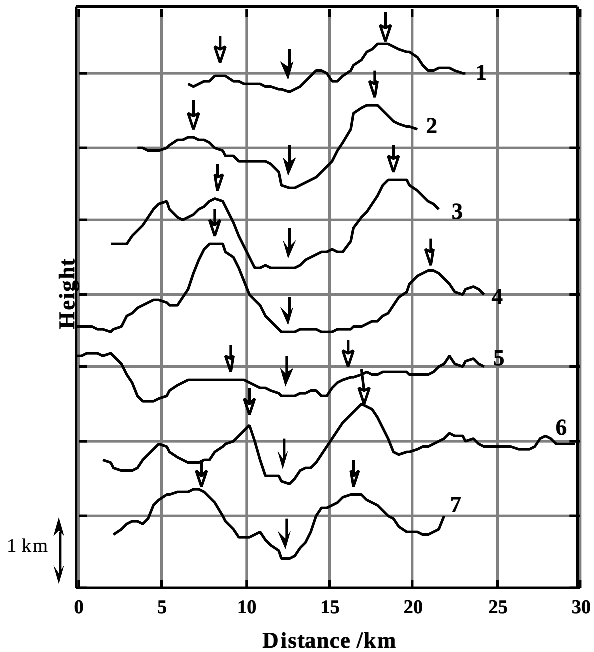

Figure 2: Profiles 1 - 7, System II.

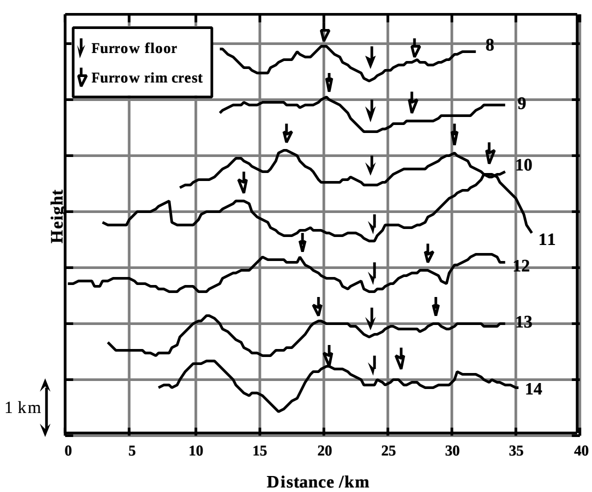

Figure 3: Profiles 8 - 14, System I.

Galileo observations of ridges and scarps on Callisto: Galileo observations of Asgard (12) indicate that the transition from the scarp zone to the trough zone is less distinct than expected. The interiors of some of the troughs furthest from the structure center have inward-facing fault bocks, which may be rotated. The scarps around Valhalla range from 200 - 300 m high (12), smaller than the rims of the Ganymede furrows. The morphology of the scarps is very different from that of the Galileo Regio furrows. Although the rims of both are sinuous, the Valhalla scarps are very narrow, whereas the furrow rims are relatively wide compared to the furrow floor. Galileo images have shown that the surface around Valhalla appears to be buried by a dark mantling material and it is likely that the scarps have been modified from their original morphologies. Bright, low crater frequency material at the foot of these scarps was thought from Voyager to be volcanically or diapirically emplaced (2,13), however no indication of flow features have been observed in the Galileo images to date. Observations of the smooth nature of the interfurrow plains indicates that the bright material at the base of the scarps may be the result of mass wasting.

Discussion: Stereo observations show that slopes of Ganymede furrows are significant, but are not as steep as is predicted for normal faults. This is likely due to modification of the slopes by mass wasting or isostatic adjustment. Several of the stereo-derived profiles show a break in slope near the base of the wall which may indicate talus, and could explain why the slopes of the younger furrow set are twice as steep as those of the older, more degraded set. This observation could also be explained by isostatic adjustment; if the first furrow system formed at a time when Ganymede's lithosphere was warmer and more mobile, it may not have been able to support significant topography. Despite the different models of formation (4), the morphology of the two furrow systems is remarkably similar and appears to differ only in the degree of modification as a function of age. In both sets, the western wall is slightly steeper than the eastern wall. If System I furrows result from an impact with its center ~2000 km from the study area (4), then these scarps would be expected to be outward-facing, as is observed for the outer Valhalla scarps and expected for a model of plastic asthenospheric flow (10). The impact structure which initiated the System I furrows would have been almost as large and old as the Valhalla structure (4, 7) so comparisons are reasonable.

Summary and future work: Galileo observations of the Asgard and Valhalla structures, and the System I furrows on Ganymede, are consistent with an impact origin. System II furrows have a morphology markedly similar to that of System I. Both sets of furrows on Ganymede have shallower slopes than those predicted through graben models but this may be a result of modification by mass wasting processes or isostatic adjustment. Further evidence for isostatic adjustment comes from the rims, which are pronounced compared to furrow depths, although this could also be due to rotation of fault blocks. Future work will include analyses of other furrows in Galileo Regio and those in other regions on Ganymede (such as transitional terrain and around groove lanes), in order to further test models of origin and evolution. Further coverage of the Valhalla and Asgard basins is scheduled for the C9 orbit.

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